An Investigation of Fin and Blue Whales in the NE Pacific Ocean using Data from Cascadia Initiative Ocean Bottom Seismometers

William S. D. Wilcock
School of Oceanography
University of Washington
Box 357940
Seattle, WA 98195-7940
phone: (206) 543-6043   fax: (206) 543-6073   email: wilcock@u.washington.edu

David K. Mellinger
Cooperative Institute for Marine Resources Studies
Oregon State University
2115 S.E. Oregon State University Drive
Newport, OR 97365
phone: (541) 867-0372   fax: (541) 867-3907   email: David.Mellinger@oregonstate.edu

LONG-TERM GOALS

The long-term goals of this project are to develop, evaluate and compare techniques to estimate fin and blue whale locations and densities from ocean bottom seismometer (OBS) data and thus enable the research community to better utilize the increasing number of OBS earthquake monitoring studies near continental margins to understand the distribution and behavior of baleen whales.

OBJECTIVES

Ocean bottom seismometers deployed for regional earthquake studies typically record signals at sample rates of ~50 to >100 Hz and thus provide an opportunity to monitor the 16-Hz calls of blue whales and the 20-Hz call of fin whales. Several studies have demonstrated the potential of OBSs to detect and track fin and blue whales (e.g., McDonald *et al.*, 1995; Rebull *et al.*, 2006; Frank and Ferris, 2011; Wilcock, 2012) and obtain density estimates (Harris et al., 2013).

The Cascadia Initiative represents a major effort to improve our understanding of the Cascadia subduction zone through the deployment of 70 OBSs over 4-years from 2011-15 (Figure 1). Data from the first three years is publically available from from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) (http://www.iris.edu/ds/nodes/dmc/data) and the fourth year will be added this fall. Sample rates vary from 50 Hz to 125 Hz with the passband for the 50 Hz data extending to ~22 Hz which is sufficient to record the 20 Hz fin whale calls (centered at 19 Hz in the NE Pacific) and northeastern Pacific blue whale calls (centered at 16 Hz).
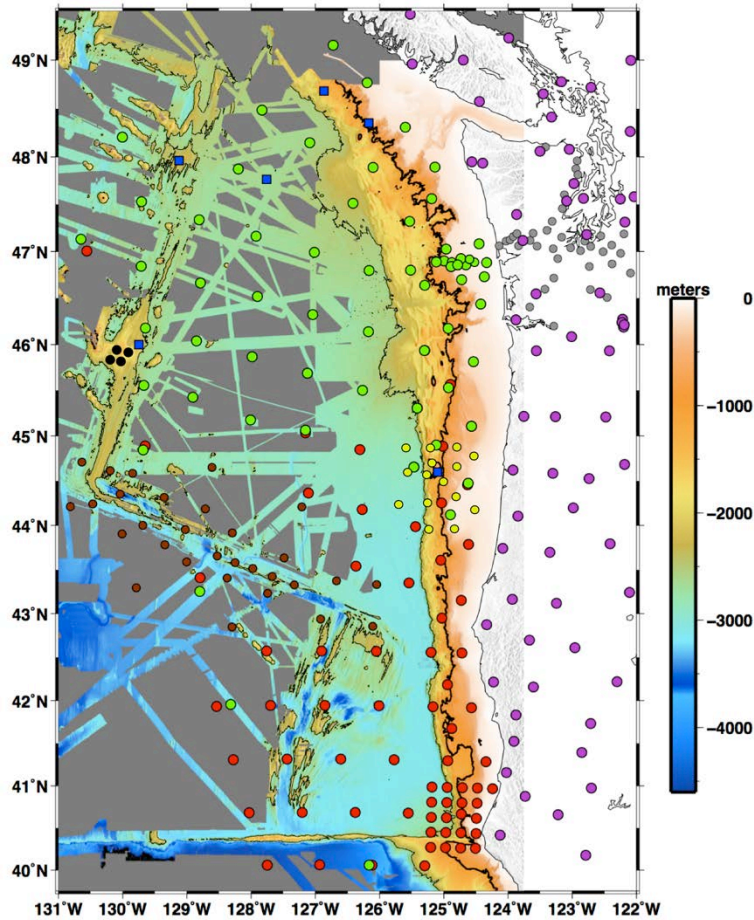
***Figure 1. Bathymetric map showing seismometer deployments with color codes as follows: 2011-12
Cascadia Initiative (green); 2012-13 Cascadia Initiative (red) and Blanco Transform experiment
(brown); 2007-9 COLZA experiment (yellow); 2007-present Axial Volcano hydrophone deployments
(black); cabled OBS (blue); and land stations (purple and grey). Cascadia Initiative deployments
for 2013-14 and 2014-15 essentially repeat the deployments for 2011-12 and 2012-13, respectively.***

The objective of this project is to develop techniques to study fin and blue whales that can take
advantage of the Cascadia Initiative experiment and other large OBS experiments. To achieve this we
will:

1. Implement established techniques to automatically detect fin and blue whale calls on the Cascadia
    Initiative OBS data

2. Develop an automated method to track blue whales using OBS network data. This will
    complement the automated method that Wilcock has already developed to track fin whales and
    provides invaluable data to evaluate techniques to localize whales and estimate density from
    single OBSs

3. Develop a multipath technique to estimate the location and density of fin whales from a single
    OBS, compare this to a method that is based on total received energy and then compare both
    methods to a third technique that uses particle motions. In shallow water where the fin whale

multipath arrivals do not overlap, neither the multipath or particle motion techniques are applicable to estimate ranges so we plan to explore the use of received call amplitudes.

4. Implement and compare techniques to estimate blue whale densities based on received call amplitudes and total received energy and verify them based on call tracks.

APPROACH

1. Detections. Our approach is to apply matched filter and spectrogram cross-correlation fin and blue whale detectors to a subset of Cascadia Initiative data to generate a data set of call detections as a function of time and location across the Juan de Fuca plate. Previously, we have evaluated two methods for automatically detecting fin whales on OBS records: matched filtering and spectrogram correlation. Comparisons of the two methods on test data containing manually identified fin whale calls show that both methods work well with the matched filtering method consistently performing slightly better. To detect blue whale calls, we have implemented a spectrogram cross-correlation detector for Northeast Pacific blue whale "B" calls (Mellinger and Clark, 2000) and evaluated its performance with a test data set.

2. Blue whale tracking. Previous studies have analyzed small data sets and presented methods to track blue whales based the on modeling relative arrival times and, in some studies, amplitudes (McDonald et al., 1995, Stafford et al., 1998; Dunn and Hernandez, 2009; Frank and Ferris, 2011) and have successfully tracked blue whales at ranges up to 40-50 km from the nearest OBS (Dunn and Hernandez, 2009; Frank and Ferris, 2011). Our approach is to develop an automated method suitable for large data sets. Since the Cascadia Initiative OBS enclose a large area our approach is first to attempt to track the blue whales using automatically picked travel times obtained from spectrogram cross-correlation and then if this proves infeasible because the calls are not detected on sufficient OBSs explore the use of amplitudes to constrain the range (McDonald et al., 1995; Frank and Ferris, 2011).

3. Fin whale density estimation. We are using two approaches to estimate fin whale densities. First, we will use multipath spacing and received amplitudes to estimate the range of calling whales from single OBSs (McDonald and Fox, 1999). We will use an extensive data set of existing tracks at the Endeavour to ground truth the techniques. In shallow water (<~750 m) the spacing of multipaths is too small to identify distinct arrivals and so we plan to explore the use of range estimation techniques based on modeling the amplitude of calls. We will also explore the possibility of extracting overlapping multipath arrivals using an autocorrelation method described by Valtierra et al. (2013). Density of calling whales can be estimated using the approach of Marques et al. (2012).

Second, we will also apply the single-hydrophone methods developed by Mellinger, Thomas, Küsel, and others (e.g. Mellinger et al., 2009; Küsel et al. 2011, Helble et al., 2013) to estimate density from total received energy in specific frequency bands. In essence, the method uses whale calling rate and source level, combined with acoustic propagation modeling, to estimate the amount of acoustic energy that would be received at a given sensor from a whale. This is combined with the density of whales in an area and distributions of these parameters (call rate, source level) in a Monte Carlo model to estimate the total energy received as a function of whale population density. The actual received energy is then measured and applied to the inverse of this function to estimate the actual population density for a given time period.

An important component of our study will be an effort to validate our two techniques by comparing them with each other and also with a third technique based on particle motions developed by European researchers (Harris *et al.*, 2013). For the comparisons, we will start with a single OBS in an acoustically simple mid-plate environment and then expand the comparison to consider OBSs in a range of environments.

4. *Blue whale density estimation.* Because the duration of blue whale calls is too long to separate distinct multipath arrivals, the two alternative techniques for estimating densities from single OBSs are to model amplitudes and to apply the total received energy method described in Task 3. The call energy for blue whales is primarily in the 14-17 Hz band which is sufficiently distinct from the 19-25 Hz fin whale band to support the technique even though the received energy from blue whales is anticipated to be substantially lower than for fin whales. As for fin whales, our approach to comparing the two techniques will be to initiate the comparisons at a single acoustically simple site and the expand them to include a wider range of acoustic environments. The availability of blue whale tracks obtained by Task 2 will provide "ground truth" for the evaluations.

WORK COMPLETED

We have made substantial progress on the first 3 objectives as well as building the data sets that will enable us to address the address the 4th objective.

For objective 1, we have implemented automated procedures to download data from the IRIS DMC and have created databases of year 1 Cascadia Initiative data at both UW and OSU. We have implemented a matched filter call detection algorithm for fin whale calls and successfully evaluated it with a test data set. We have tuned a spectrogram cross-correlation blue whale detector to the fundamental frequency of blue whale calls in the Cascadia Initiative data and evaluated against calls identified by an analyst.

For objective 2, we have developed a method to track blue whales. We first apply the cross-correlation detector to all OBSs wth the detection threshold set low. Based on a manual verification of a subset of calls, we select the subset of detections above a threshold, chosen so as to minimize the number of false detections while still ensuring that each call within the network is likely detected on at least one OBS. These high-threshold detections are used as master calls to apply a multiple-animal time of arrival method to find all the detections that associate with each master call. Finally a Bayesian inversion approach (e.g., Dunn and Hernandez) is used to a generate probability density functions for the whale locations. We have evaluated the method against manual tracks for a subset of 9 OBS and are applying the method to the complete data set of the

For objective 3, we have completed the development of the automated single station multipath ranging method and evaluated its performance using data from the Endeavour segment where tracked calls are available and a mid-plate setting, where the bathymetry is less complex, but tracked calls are unavailable. The multipath ranging method uses the timing and relative amplitude of multipath arrivals to estimate range. Calls and multipath arrivals are detected automatically and compared with the modeled receive structure at a series of range steps between 0-25km from the instrument. Multipath timing is modeled using Bellhop ray tracing software and seasonal average sound speed profiles. Amplitudes are modeled using ray divergence, assuming constant seafloor properties. The range model that best matches the received signal is our best estimate of range.

At mid-plate location, where ~300m of sediment overlies a basalt basement, there is interference with the arrival that is reflected off of the basement layer. This can result in a second, slightly delayed peak, which can be higher in amplitude than the water-borne arrival due to constructive interference. To deal with this, we search for lower amplitude peaks within 0.5 seconds of non-direct path arrivals.

Amplitudes measured at the Endeavour location show a large degree of variability, which is expected at such a bathymetrically complex location. At the mid-plate location, relative amplitudes appear more stable, but do not match modeled amplitudes beyond the critical range. Range estimates improve significantly when amplitudes are extracted manually from a subset of the data, and used to constrain the amplitude model.

For the second method, which is based on total received energy, the method development was completed and applied to the deep-water Cascadia Initiative instruments. This required estimating propagation loss at each of the instruments, as well as using the received sound signal at each instrument site, using noise-removal techniques to help eliminate narrowband shipping noise and wideband environmental noise (principally from wind/waves), and then estimating the sound level in the fin whale band in the result. There was also a complication in that the instruments were ocean-bottom seismometers rather than hydrophones; to handle this, the Zoeppritz equations describing how pressure waves pass from water to rock were used.

For objective 4, we have started the processes of compiling a database of blue whale tracks to evaluate the density estimation methods.

RESULTS

Results from this project were presented in 3 talks at the 7th International Workshop on Detection, Classification, Localization, and Density Estimation (DCLDE) of Marine Mammals using Passive Acoustics (Mellinger et al., 2015; Weirathmueller et al., 2015; Wilcock et al., 2015) and will be presented in two talks at the 21st Biennial Conference on the Biology of Marine Mammals (Mellinger et al., 2015; Wade et al., 2015).

Figure 2 shows range estimation examples from the Endeavour segment and mid-plate datasets. At the Endeavour location, most of the errors in range are the result of complex bathymetry: there is a large degree of variability in both amplitude and timing of received arrivals that results in range ambiguities.
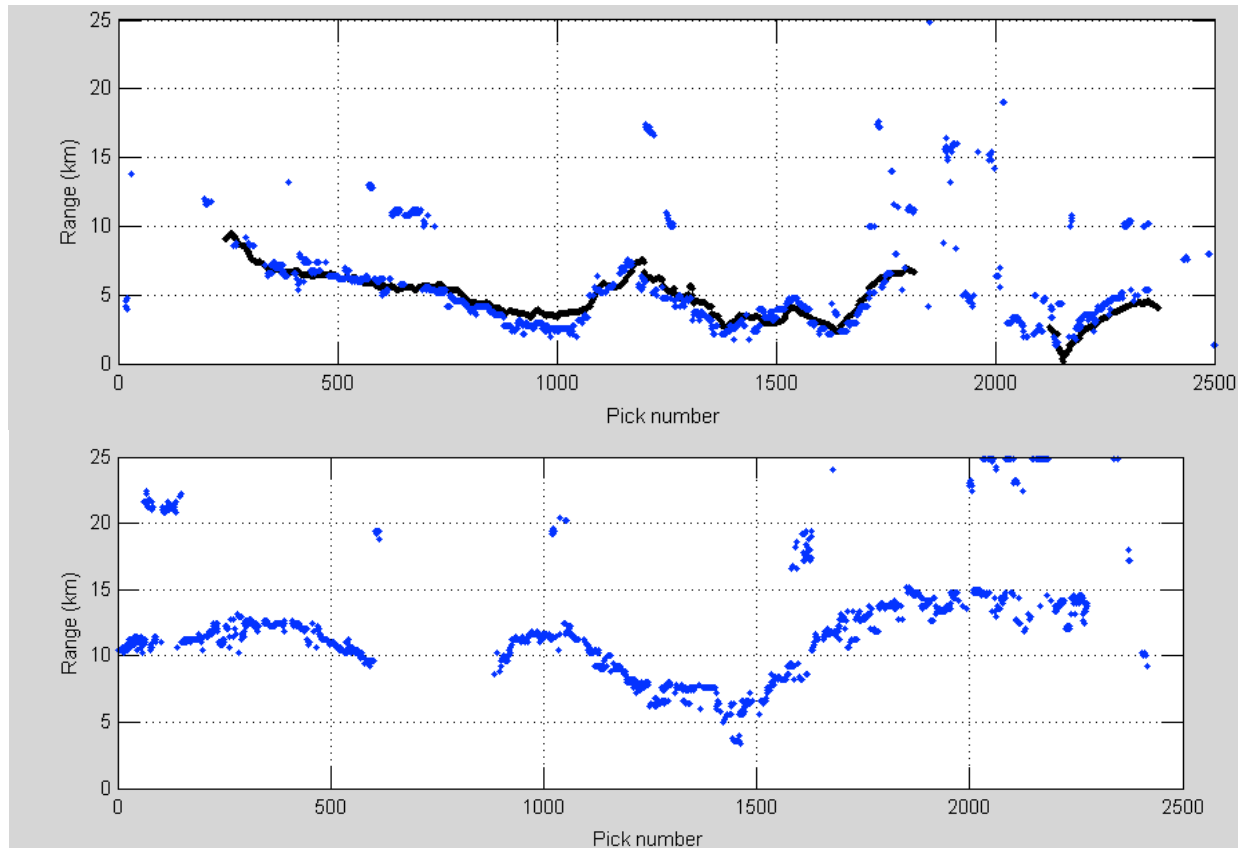

Figure 2. Examples of ranging results for a series of calls at each test location. The upper panel shows a series of calls at the Endeavour segment. Independently determined ranges are shown by black dots and ranges derived using the multipath ranging method are shown by blue dots. The lower panel shows a series of calls at the mid-plate location. There are no independently determined ranges at that location, but multipath ranges are shown by blue dots.

Figure 3 shows uncertainties in range estimates as a function of independently derived ranges from tracked calls.
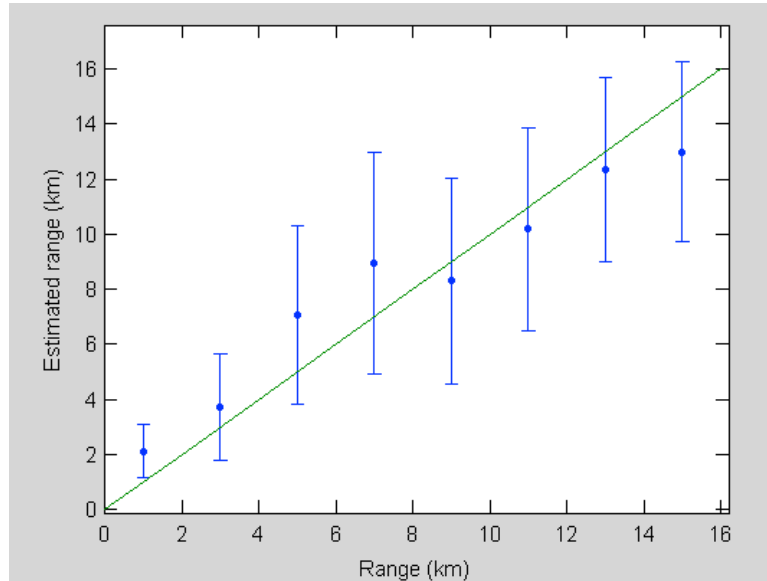

Figure 3. Estimated range vs. tracked range at the Endeavour segment location. Each blue point shows the mean range within that 2km range bin, with error bars indicating standard deviation.

Figure 4 shows histogram plots for both locations where the number of detections are binned by range. One of the assumptions when using point transect distance sampling is that the animals are uniformly distributed. Results from both of these datasets indicate that this assumption does not hold.
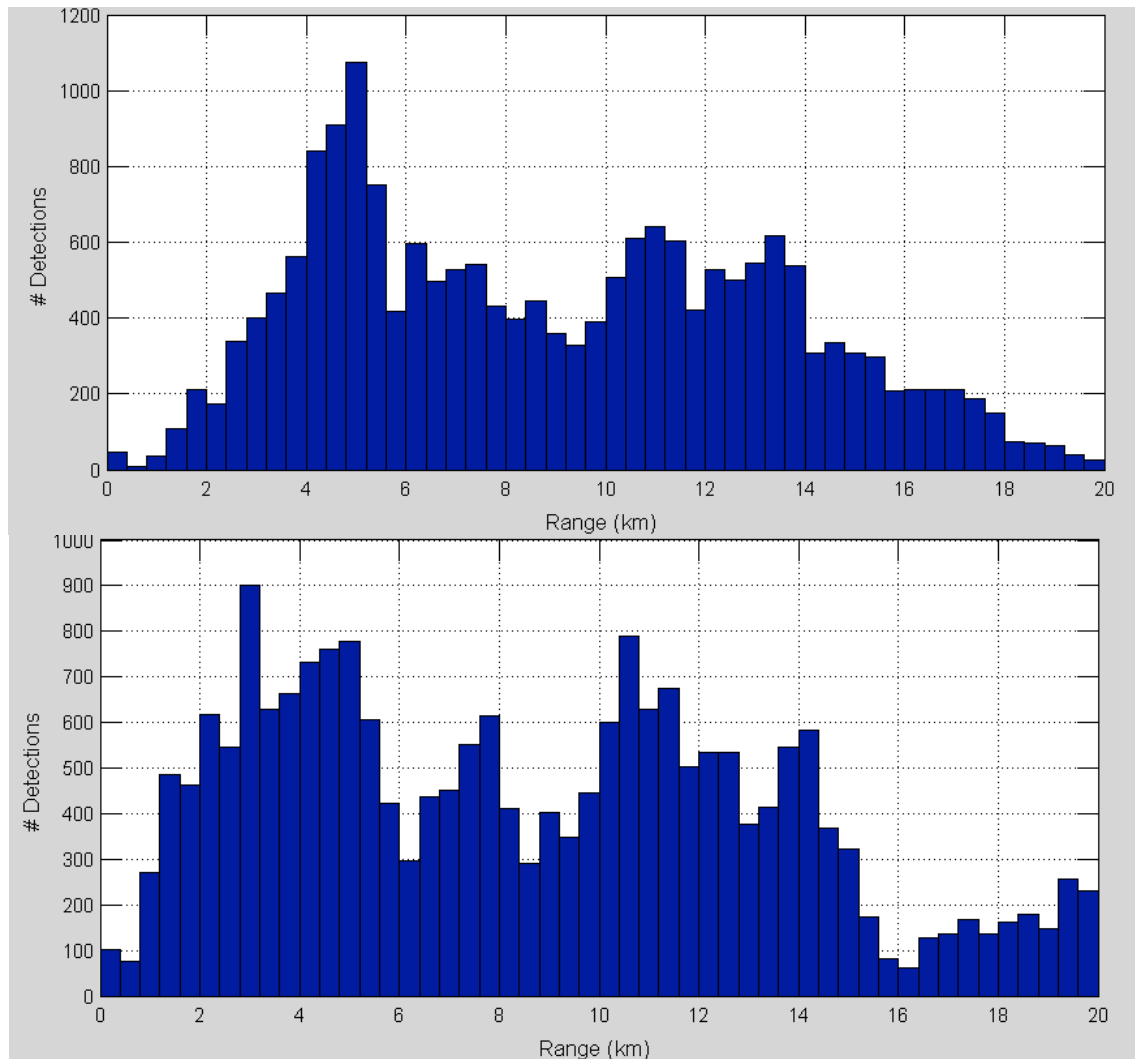

Figure 4. Range distribution of detections at the Endeavour segment (upper panel) and at the mid-plate location (lower panel). Detections are binned in 400 m increments.

Figure 5 shows a blue whale location obtained using a grid search method to matching detection times on 8 stations assuming a master detection on station J36A. The best location fits detections on 6 stations while failing to fit any of the detections on stations J43A (weak detections and possibly spurious) and J45A (stronger detections and likely from a different whale). We found that the method sometimes fails because it matches weak detections at the expense of strong ones, matches strong detections from two or more whales or matches different calls from the same whale. In order to address this problem we have modified the method to penalize solutions that do not place the higher amplitude detections close to the location and we are exploring methods that consider the call sequence when associating calls between OBS (e.g., ensuring that the 2nd call in a sequence on one OBS is not associated with the 3rd call in the sequence in the 3rd OBS).
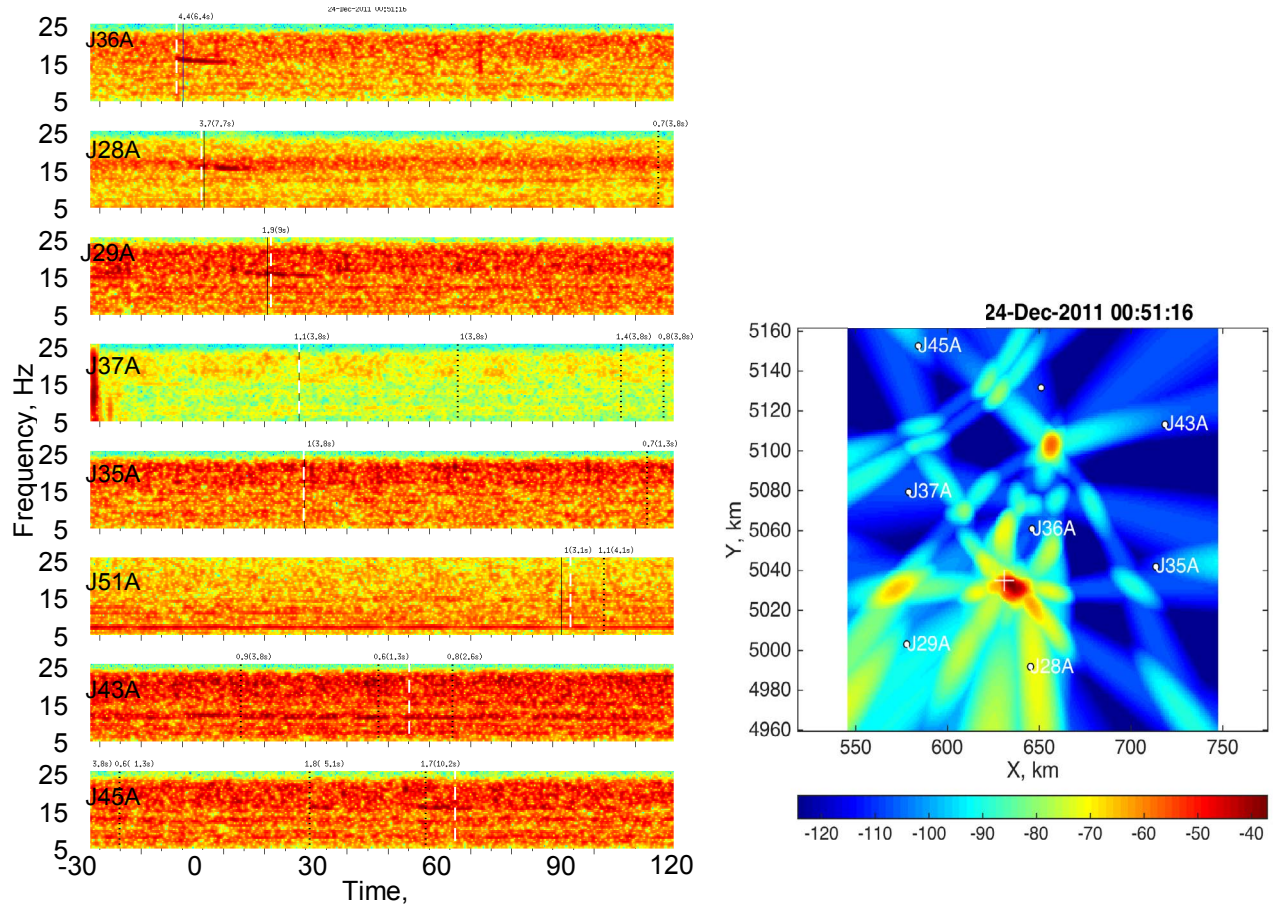

Figure 5. Example of blue whale location. (left) plot show spectrograms for 120 s of data recorded by 8 OBSs labeled with the station name showing detections from spectrogram cross-correlation detector (solid and dotted black lines labeled with the detection amplitude and duration in seconds in parentheses with the solid lines for detections incorporated in the preferred location) and predicted times for the preferred location as white dashed lines. Blue whale B calls are clearly visible on stations J36A, J28A and J29A as down-swept signals around 16 Hz lasting ~10 s. Weaker detections are visible on other OBSs (right) Contour plot a the un-normalized probability density showing stations (labeled white circles) and the preferred location (white cross).

Figure 6 shows an example of a blue whale track obtained by the automated method. Over ~40 hours the whale swims 200 km south through the network with two short gaps in calling. We are presently using a data set of manually tracked calls to evaluate and optimize the automated method and are compiling automated tracks and calling densities for the full year 1st Cascadia Initiative network (Wade et al., 2015).
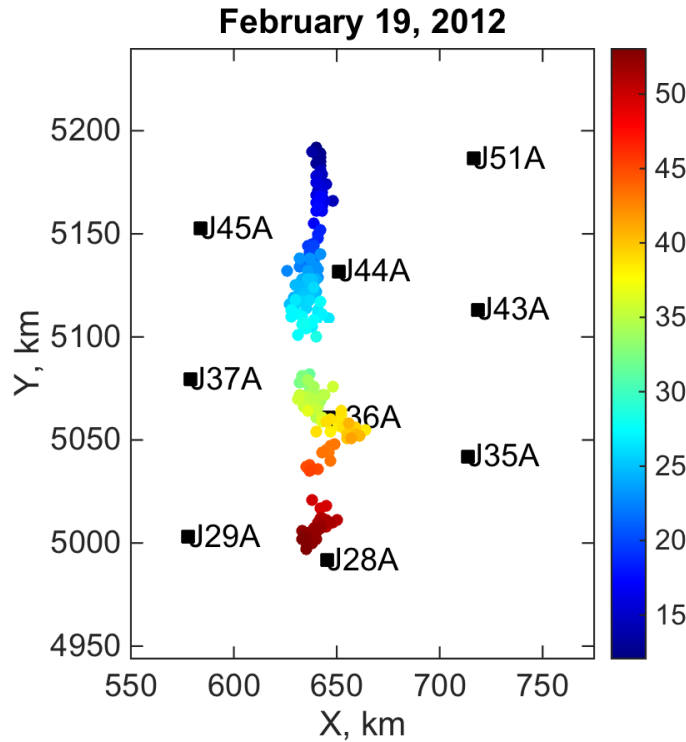

Figure 6. Example of a blue whale track that extended over 40 hours on February 19-21 showing the whale locations color coded by time (hours relative to the start of Feb 19) and stations (labeled black squares). The whale swam south through the network at an average speed of 5 km/hr.

The band-limited energy estimation method was applied to deep-water seismometer data from the Cascadia Initiative in 2011-12. This revealed a problem with this dataset, in that there were relatively few instruments that both worked well (many instruments had technical problems), and also were deployed in deep water where sound is received from a relatively large area and propagation modeling works well. Despite these problems, six seismometers were available and were analyzed for fin whale density.

Figure 7 shows a spectrum of received fin whale energy, while Figure 8 shows a map of fin whale density over the study area during one week of the deployment. The results in Figure 8 reveal an issue we are currently addressing, namely that the calculated densities are very small relative to what was expected.
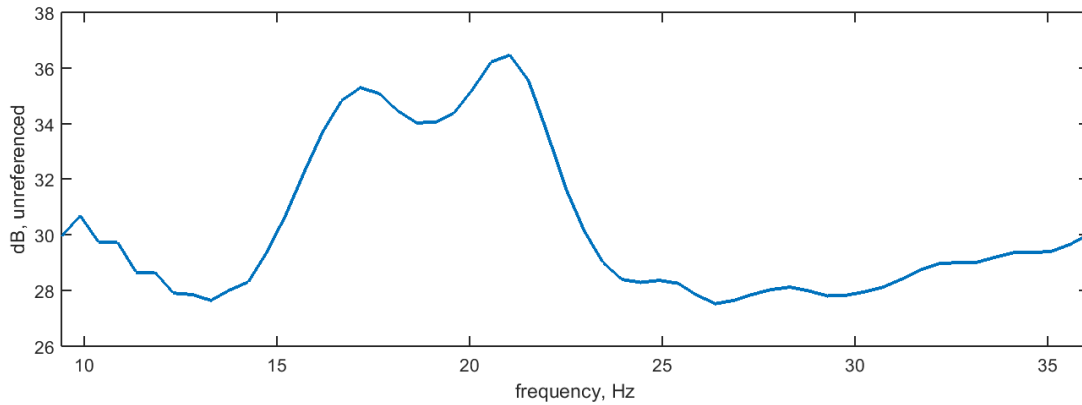

Figure 7. Spectrum of received sound for one instrument (instrument FN14A, 2011-Dec-17, 0425Z). The rise in energy in the 15-23 Hz band represents the sound received from singing fin whales in the area surrounding the seismometer.
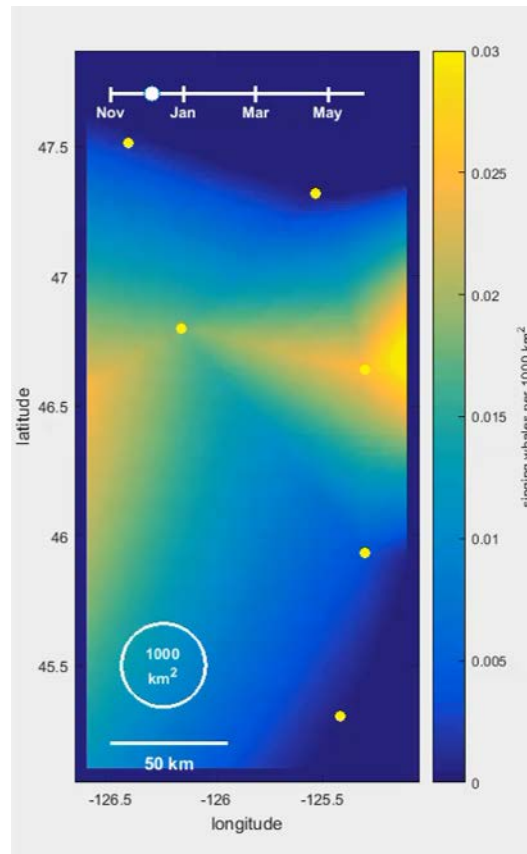

Figure 8. Density of singing fin whales in the deep-water region of the Cascadia Initiative in early December 2011. This is one frame of a video showing density throughout the year that was shown at the 2015 DCLDE workshop. Color represents fin whale density; the circle represents an area of 1000 km², which is used in the color scale's unit of density.

IMPACT/APPLICATIONS

There is a movement within the US and global marine seismic communities to expand the number of ocean bottom seismometers available for earthquake monitoring projects and to undertake experiments with larger footprints and longer durations. The techniques we are developing will allow the Navy and other interested parties to take full advantage of OBS experiments of opportunity in areas that interest them to understand the distribution and behavior of fin and blue whales and potentially other baleen whales if the sampling rate of OBSs are in the future extended to higher frequencies.

RELATED PROJECTS

Wilcock's group previously received ONR funding (N00014-08-1-0523) to develop an automated method to track fin whales and apply it to a small scale (~10-km aperture) network of OBSs on the Endeavour Segment of the Juan de Fuca Ridge. Over 150 fin whale tracks ranging in duration from ~1 hour to 1 day were obtained and are being utilized in the work we propose to validate techniques that determine fin whale ranges and densities from single OBSs.

Mellinger and colleagues have received ONR funding (N00014-11-1-0606) for developing a density estimation method for calling fin whales that relies on the total sound energy received at a single hydrophone. The method is being applied to a case study off Portugal and is being compared to a technique that utilizes three-component particle motions to locate proximal whales and estimate density. Both techniques would profit from testing on a different population of whales in a different acoustic environment. The total received energy method can also be applied to calling blue whales and potentially any other species for which there is a frequency band in which call energy rises substantially above background noise. Simpler preliminary versions of this model have already been applied to estimating the population density of fin whales in the mid-Atlantic (Mellinger *et al.* 2009) and leopard seals off the Antarctic Peninsula (Klinck *et al.* 2012).

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